JOHNS HOPKINS APPLIED PHYSICS LABORATORY

NASA TNO KNMI

CHAPS-D
COMPACT HYPERSPECTRAL AIR POLLUTION SENSOR

CHAPS: A Compact Hyperspectral Imager for Atmospheric Composition Space Remote Sensing

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KNMI: Pepijn Veefkind, Pieternel Levelt

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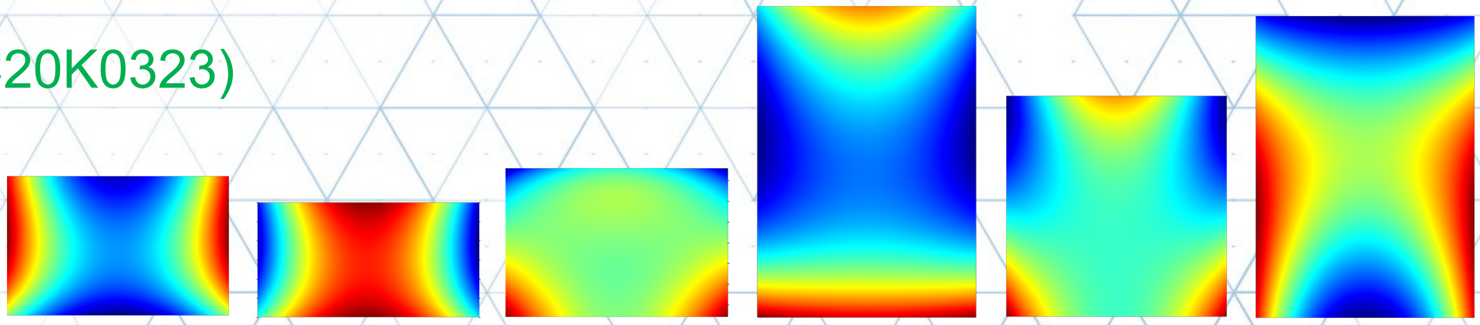
APL and TNO internal R&D

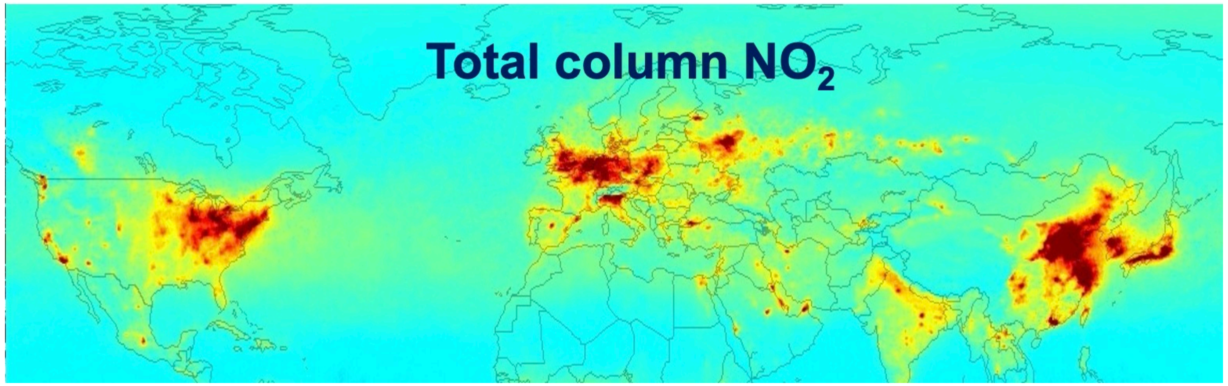
TNO = The Netherlands Organization for Applied Scientific Research (TNO), Delft
KNMI = Royal Netherlands Meteorological Institute and University of Technology Delft



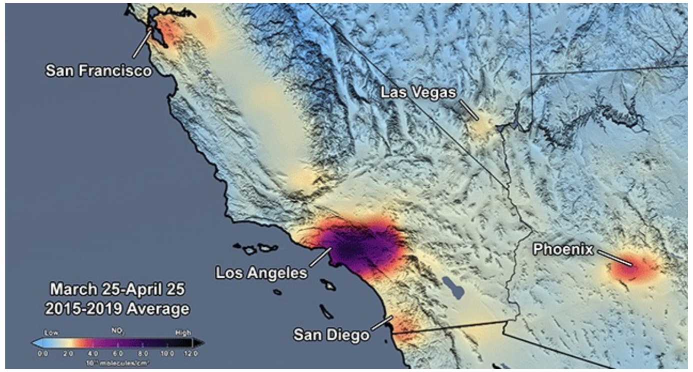
CHAPS-D mirror shapes (deviations for parabolas)

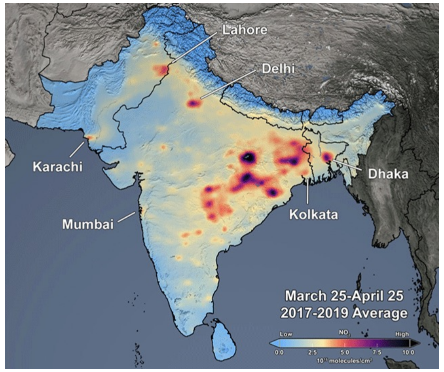
CHAPS improves spatial/temporal resolution, important for understanding air pollution emissions and evolution

Air pollution spans the globe but is highly correlated with human population.



Covid-19 lockdowns led to a dramatic, if temporary, reduction in air pollution.





- Air pollution has negative impact on human and ecological health
- Changes in pollution driven by changes in energy usage, technology, and regulation
- NO_2 and CO_2 emissions are correlated
- Air pollution disparities reflect racial, ethnic, and income inequality in the US
- Need for high-spatially and -temporally resolved measurements of air pollution
- CHAPS is
  - miniaturized
  - targeted
- CHAPS can
  - provide more cloud-free observations
  - effectively separate clustered point sources in polluted regions
  - understand mixing of emissions, their transport and transformation; short-term evolution of pollution plumes

Freeform optics enables miniaturization

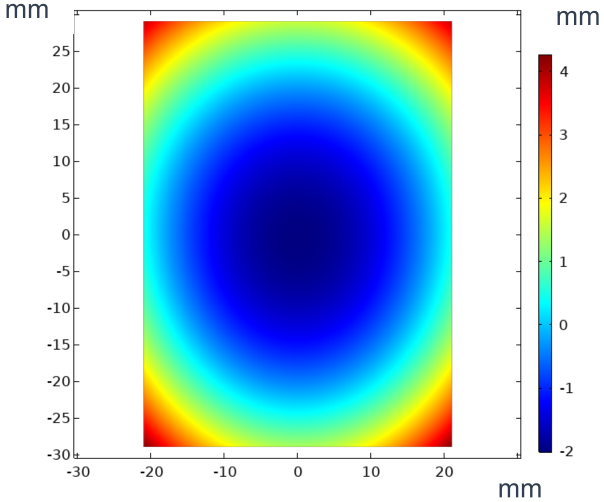
Polaroid SX-70 (1972–1981)

https://www.eyemartexpress.com/lenses

TROPOMI (launched 2017) with TNO optics • State of the art, providing global surveys

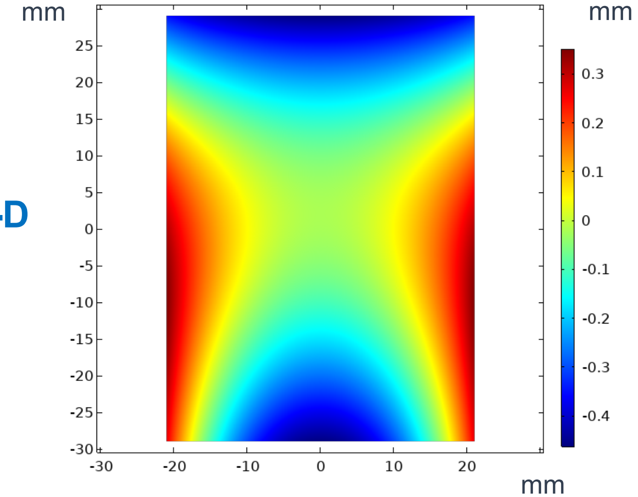
- Freeform optics: *An optical surface that lacks translational or rotational symmetry*
- Freeform optics offers superior optical aberration correction, compared to spherical and aspherical alternatives
- In an imaging spectrometer, this has several advantages
  - spectral band broadening: increased spectral range
  - spatial broadening: increased slit length (and swath width)
  - increased compactness: unprecedented miniaturization

Imager mirror #3: Surface shape



Example CHAPS-D freeform mirror

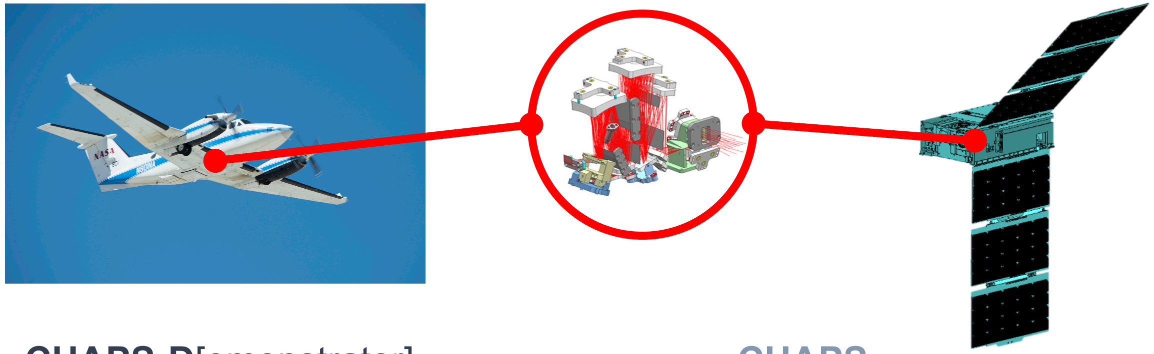
Imager mirror #3: Deviations from parabola



Proposed investigation

- Design, fabricate, calibrate, and test prototype CHAPS-D, conforming to 6U constraints and space requirements, where reasonable
- Conduct ground-based, zenith-sky measurements as a real-world test of the instrument under controllable conditions and ambient pollution at GSFC
- Fly CHAPS-D on the NASA B200 King Air from LaRC, making nadir observations of tropospheric pollution
- Retrieve tropospheric NO_2* vertical column density using well-established techniques, demonstrating end-to-end capability
- Compare retrieved NO_2* (and others) with correlative measurements on the ground, potentially from another instrument co-manifested on the aircraft and operational space products from OMI and TROPOMI
- Use lessons learned to improve the CHAPS design and define the spacecraft interface requirements

* Also SO_2, ozone, glyoxal, clouds



CHAPS-D[emonstrator]
(this IIP)
Altitude ~8 km
Spatial resolution ~40 m

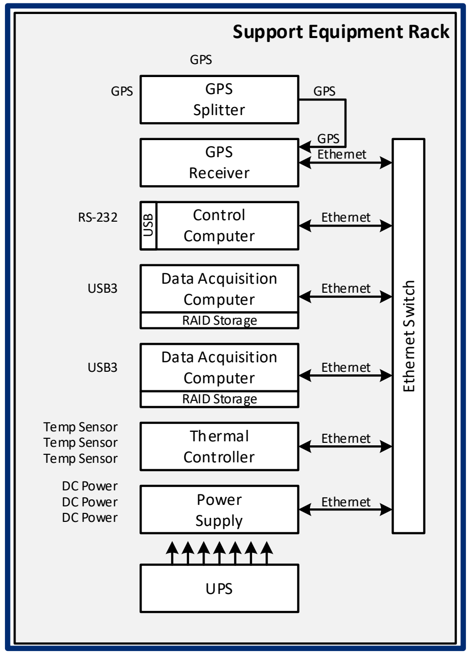
CHAPS
(future project)
Altitude 400–600 km
Spatial resolution ~1 km

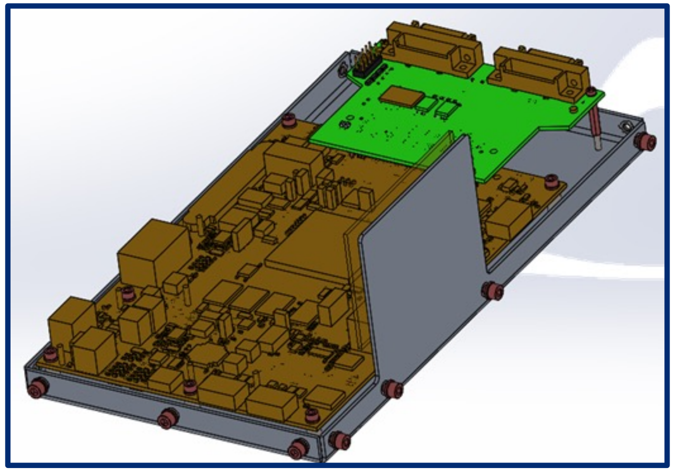
Driving requirements: Science-quality measurements

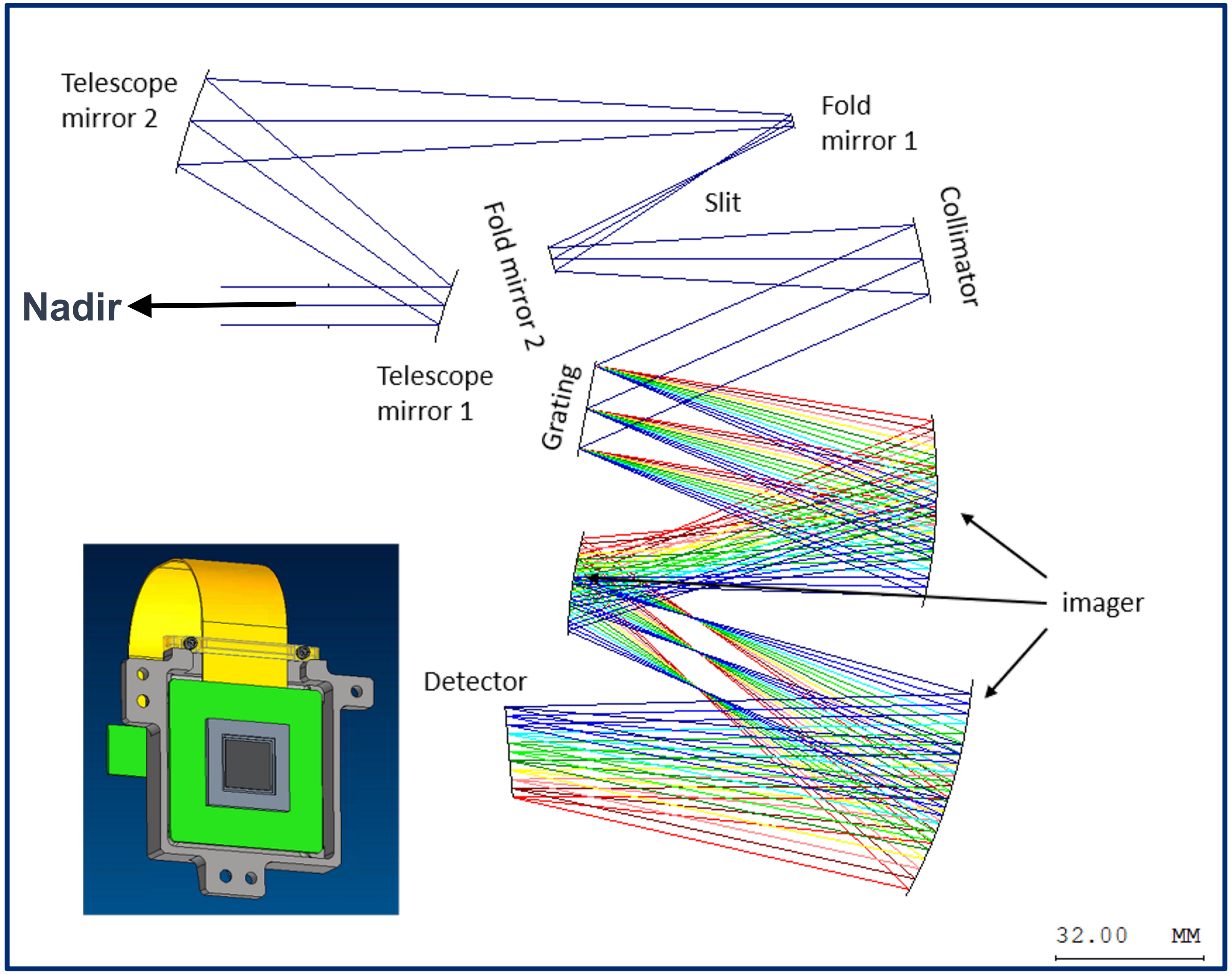
Parameter	Value	Driver
Spatial sampling	<1 km (space) <40 m (aircraft)	Adequate isolation of individual pollution sources
Swath width (across track)	100 km (space) 400 m (aircraft)	Adequate coverage of urban environments
Wavelength range	300–500 nm	Retrievals from NO_2, SO_2, ozone, glyoxal, cloud absorption features in this range
Wavelength resolution	0.6 nm	Needed to resolve trace species absorption features
Spectral oversampling	>3x	Needed to resolve trace species absorption features
Signal-to-noise ratio	>500	SNR required for spectral resolution and oversampling of NO_2

CHAPS-D subsystems

- Optics and detector package are being developed to fit within a 6U CubeSat payload volume for a future space mission
- Camera electronics and support equipment are being developed specifically for aircraft use, to be replaced by high-TRL electronics for a future space mission







CHAPS-D Support Electronics

APL – Software

COTS – Hardware

CHAPS-D Camera Electronics

APL – Interface Electronics and Firmware

COTS – FPGA Board

CHAPS-D Detector Package

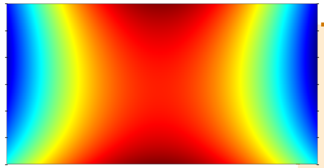
APL – Design

APL – Manufacturing

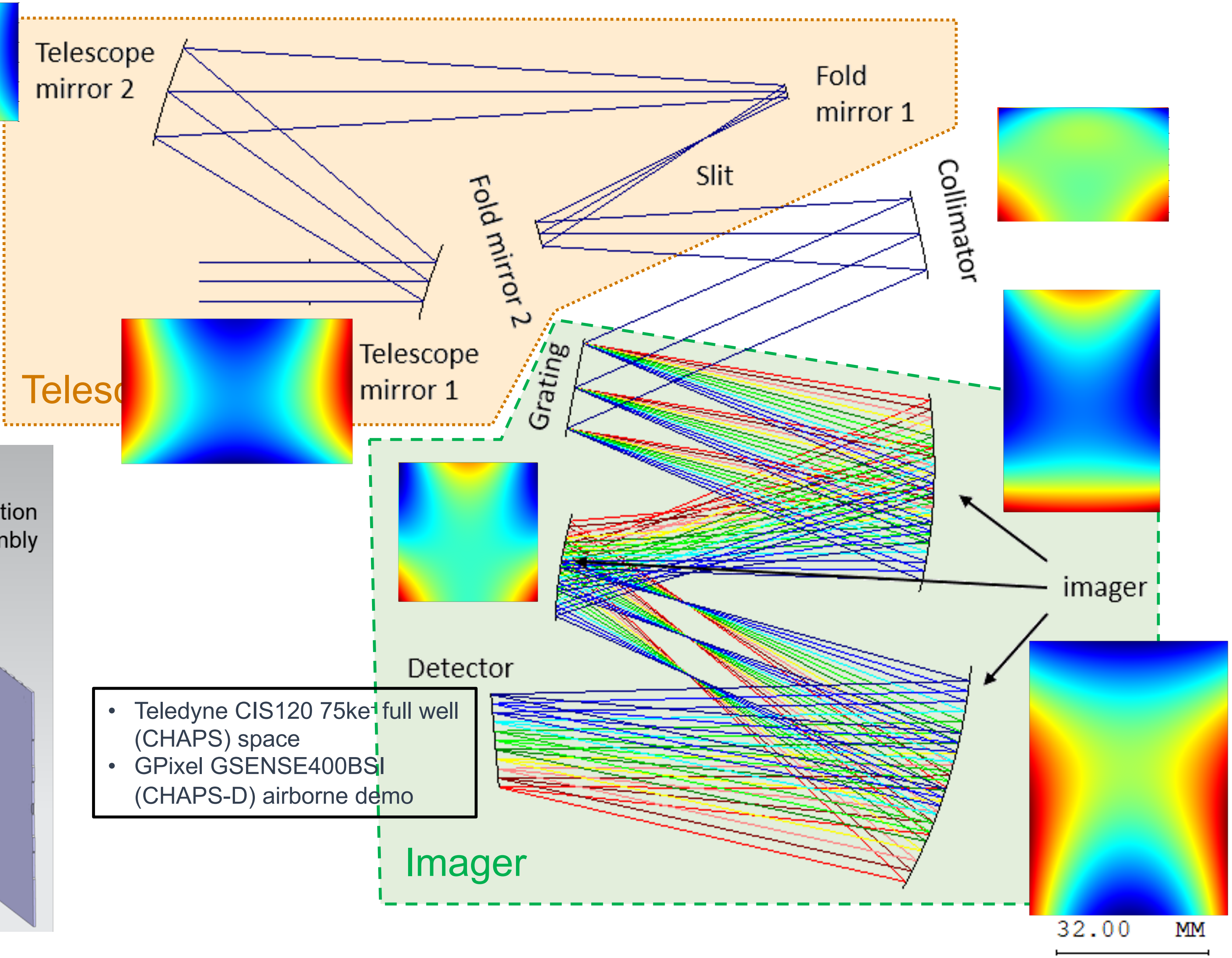
CHAPS-D Optics

TNO – Optical Design, Housing Design

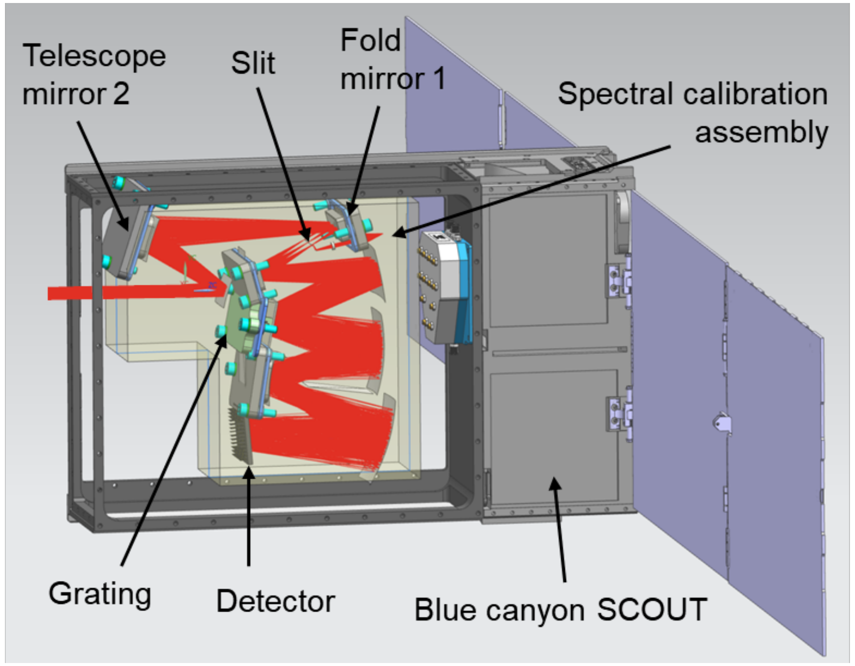
APL – Housing Manufacturing



Freeform mirrors (deviations from parabolas shown)



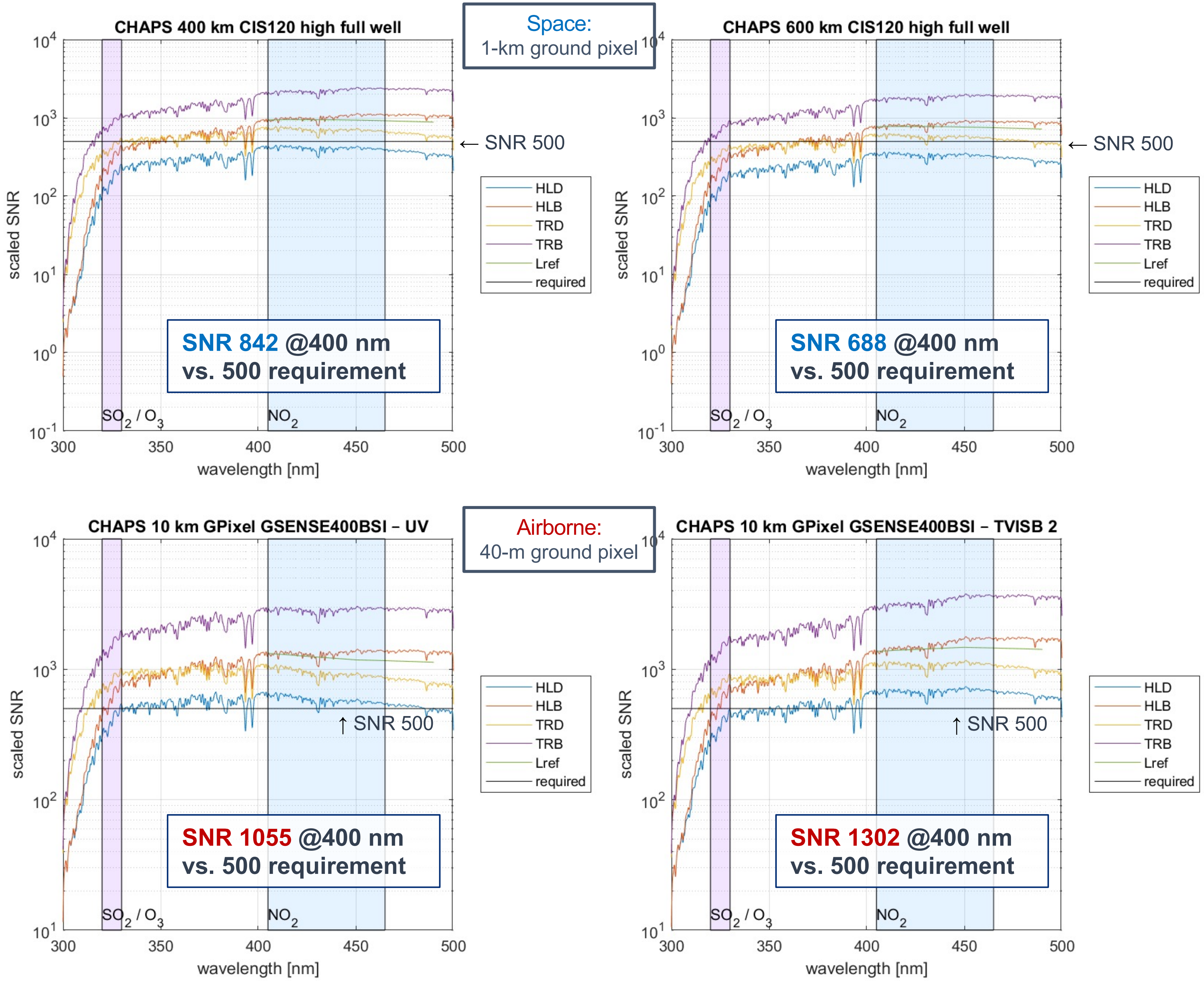
- Teledyne CIS120 75ke⁻ full well (CHAPS) space
- GPixel GSENSE400BSI (CHAPS-D) airborne demo



Preliminary design

Preliminary design meets performance requirements

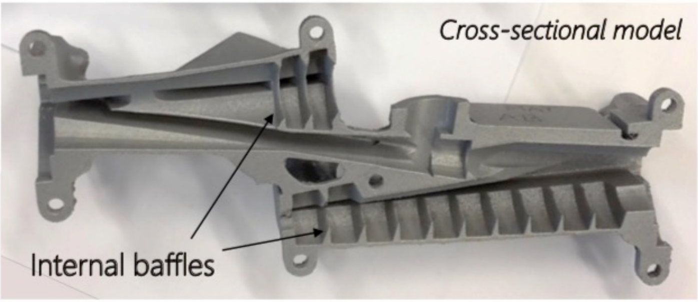
- optical layout
- system etendue
- optical throughput
- spot size and variation
- keystone/smile
- spectral/spatial resolution
- stray light
- bright–dark scene contrast
- grating orders
- polarization
- mechanical tolerance analysis
- where possible, computing impacts on L2 retrievals



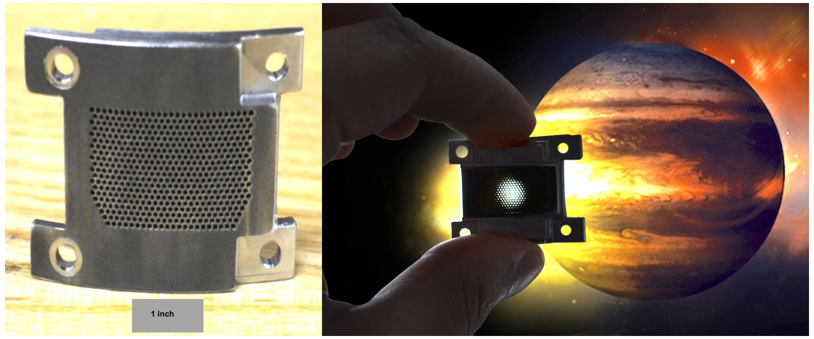
Leveraging additive manufacturing (3-D printing)

- Additive manufacturing (AM) provides a number of potential advantages
  - Using topology optimization for mass, thermal, vibration, and (additive) manufacturability
  - Internal baffling fine structure (critical for stray light control) is very amenable to AM
  - Reduces complexity of housing (idea: AM entire mechanical structure and light baffling in one go)
  - AM of the mirrors would reduce mass
  - Reduces manufacturing time and cost of future instruments
- Ongoing work that benefits CHAPS-D*
  - Selection of next-generation aluminum alloy for space (optical) applications: Strength, compatibility with coatings
  - Design of light baffling surface structures

*APL and TNO internal funding

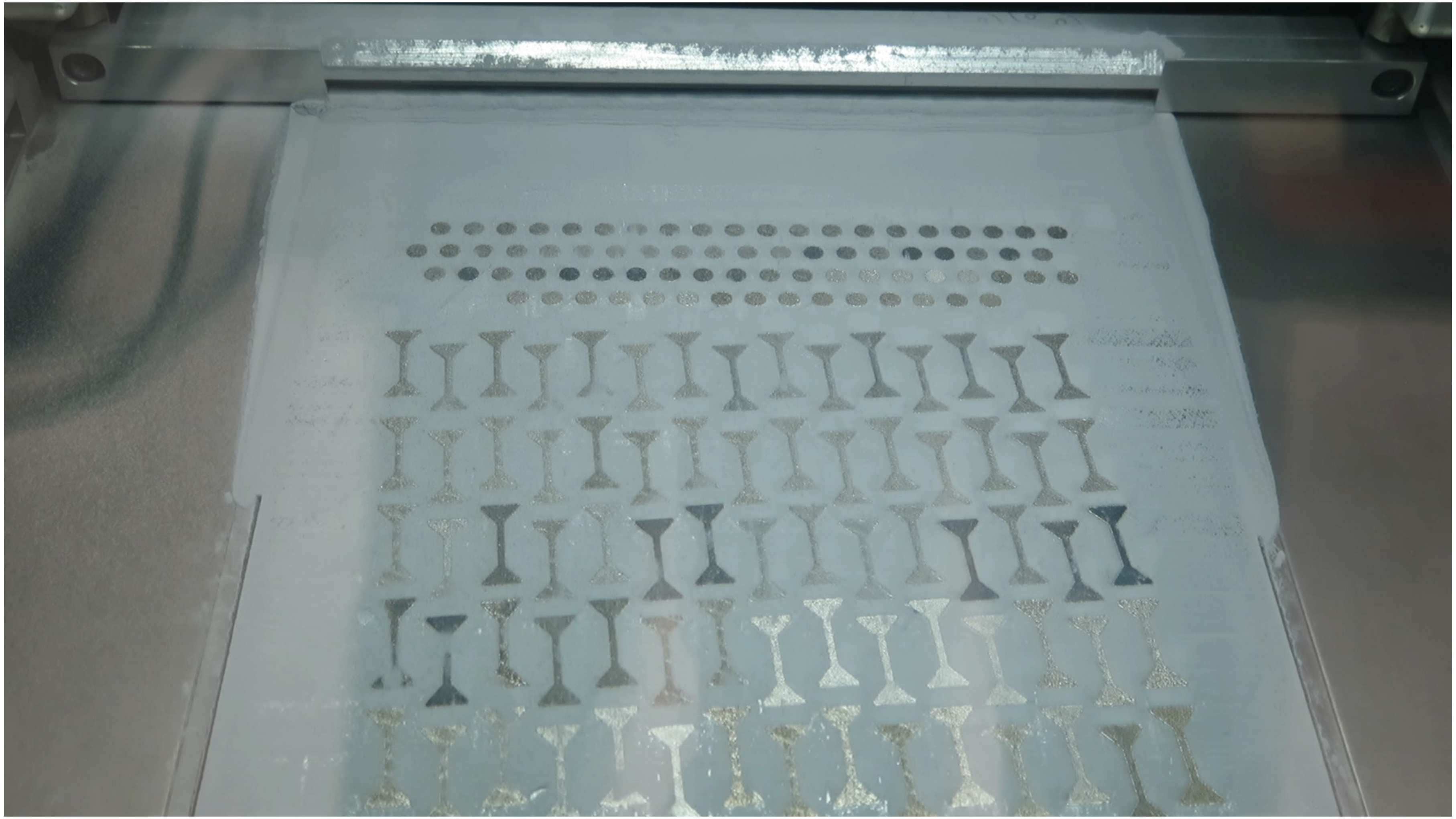


Telescope internal baffling (TNO for ESA)



JUICE JOEE Collimators (APL for NASA)

Metal AM: Laser melting video



Mechanical structure incorporates additive manufacturing

- Athermal design
- Design optimized for additive manufacturing (3-D printing)
  - High-strength aluminum alloy
  - Monolithic housing integrating multiple functionalities
  - Integrated stray light baffling (including baffles, vanes, and surface textures)
  - Integrated struts, cable tie hooks
  - Post-machining using 5-axis milling
- Topology optimization: Iterative algorithm that generates freeform (not referring to the optics) designs according to an objective and constraints
- Half-open structure for cleaning, inspection, and coating
- Optical elements mounted directly on assembly tolerances
- Alignment using 5- or 6-DoF manipulation of the detector

Component	Traditional	AM
Housing		•
Mirrors	6	2
Mirror mounts*		8
Slit	•	
Grating mount	•	
Detector mount	•	
Earth baffle*		•
Stray light baffles*		•
Thermal pathways*		•
Structural pathways* (struts)		•

* integrated into housing

AM alloy selection

- Developing use of "next-generation" Al alloys
- Key parameters considered
  - Strength
  - Stiffness
  - Dimensional stability
  - Thermal conductivity
  - CTE
  - Porosity
  - Particle count after printing
  - Printability
  - Compatibility with NiP plating, diamond turning (for mirrors)
  - Compatibility with black coatings
- Candidate materials selected for test
  - 6061 RAM2
  - A20X
  - Scalmalloy
  - 7A77

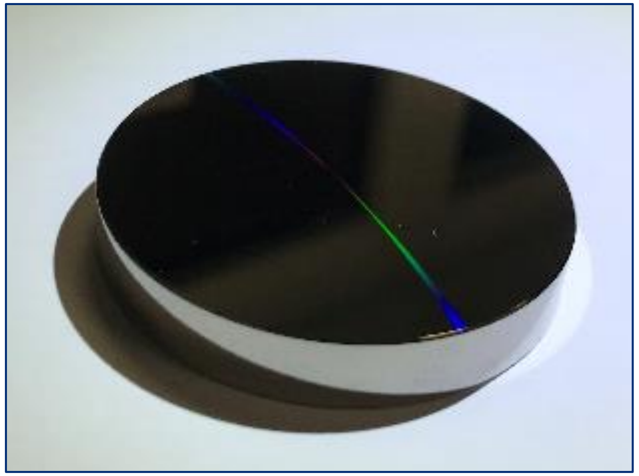
Candidate AM aluminum alloys

Material	Yield (MPa)	Elong. (%)	Th. Cond. (W/mK)	Composition
AlSi10Mg	230	11.5	173	Si: 10% Mg: 0.35%
Elementum 6061 RAM2 2% ceramic	285	12.5	119	Mg: 1.0% Si: 0.6% Cu: 0.3% Fe: 0.7%
NanoAl Addalloy 5T 5000 Series	380	15	NA	Mg: 4.0% Zn: 3.0% Mn: 0.8% Zr: 0.6%
Elementum 2024 RAM2 2% ceramic	400	10	NA	Cu: 4.6% Mg: 1.4% C: 1.0% Mg: 0.7%
AMT Ltd A20X (similar to A205 castable alloy)	440	13	NA	Cu: 4.6% Ti: 3.4% B: 1.4% Ag: 0.8%
Carpenter Additive Scalmalloy	490	14	NA	Mg: 4.5% Sc: 0.7% Mn: 0.5% Zr: 0.4%
Elementum 7050 RAM2 2% ceramic particles)	507	5%	NA	Zn: 6.2% Mg: 2.3% Cu: 2.3% Zr: 0.12%
HRL Labs 7A77	537	10	NA	Zn: 5.3% Mg: 2.5% Cu: 1.6% Zr: 2.0%
NanoAl Addalloy 7S	630	6	130	Zn: 5.6% Mg: 2.5% Cu: 1.6%

AM optical components compatible with post-processing

Scalmalloy, A20X compatible with mirror post-processing

3-D printed mirror "blanks"



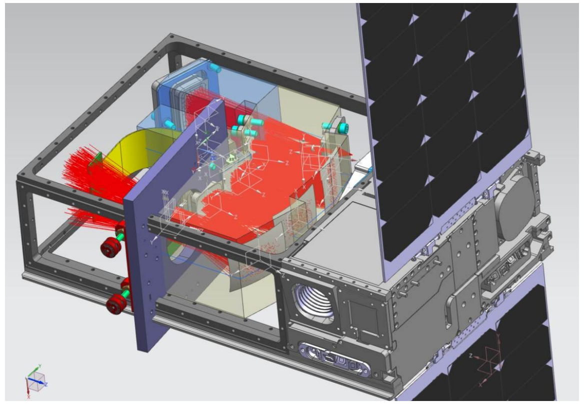
AM Scalmalloy mirror (NiP plating and polishing by TNO)

AM-enabled integral light baffles

Shown in future presentation, pending IP disclosure review

Summary

- CHAPS is a compact imaging spectrometer for atmospheric composition measurements
  - Freeform optics, leveraging ESA TROPOMI heritage
  - Additive manufacturing utilized for mechanical structure and (maybe) mirrors
  - Designed to 6U CubeSat constraints
  - Demonstration focused on air pollution
- CHAPS-D currently in design phase
  - Preliminary optical design complete
  - Mechanical, electronics design ongoing
  - PDR fall 2021; CDR winter 2021/2
  - Ground-based, airborne demonstration 2022/3



CHAPS-D instrument within CubeSat form factor

CHAPS-D additively manufactured mirror “blanks”

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